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Sustainability study of hydrogen pathways for fuel cell vehicle applications

Jenn-Jiang Hwang

Department of Greenergy, National University of Taiwan, Tainan, Taiwan

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ABSTRACT

The present work has conducted a comprehensive life-cycle analysis of energy consumption and greenhouse gas (GHG) emission for various fuel/vehicles systems. Focus is placed on the hydrogen-based fuel cell vehicle (FCV) technology, while the gasoline vehicle (GV) equipped with an internal combustion engine (ICE) serves as a reference technology. A fuel-cycle model developed at Argonne National Laboratory, the GREET model, is employed to evaluate the well-to-wheels (WTW) energy and emissions impacts caused by various fuel/vehicle systems. Six potential hydrogen pathways using renewable and non-renewable energy sources are simulated, namely, steam reforming of natural gas and corn ethanol, water electrolysis using grid generation and solar electricity, and coal gasification with and without carbon sequestration. Results showed that the FCVs fuelled with solar electrolysis hydrogen have the greatest benefits in energy conservation and GHG emission reduction. However, by incorporating with the economic consideration, hydrogen from the natural gas reforming is likely to be the primary mode of production for the initial introduction of FCVs.

Contents

1. Introduction

In order to alleviate the combined threats of climate change, urban air pollution, and quick depletion of crude oil caused by petroleum-based internal combustion engine (ICE) vehicles, it is urgent to develop alternative fuel vehicles that could substantially cut the oil dependence and reduce the carbon footprint of the transportation sector [1]. With the potential of near-zero tailpipe emissions, great vehicle performance and fuel efficiency [2–4], and lack of dependence on crude oil compared to the ICE vehicles, the fuel cell vehicles (FCVs) are regarded as the next generation vehicle that could improve dramatically urban air quality, climate change, overall energy consumption and energy security [5].

E-mail address: azaijj@mail.nutn.edu.tw

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Recently, a number of fuel cell developers and automakers around the world have devoted themselves to introduce fuel cell vehicles to the market, all hoping to establish themselves as prominent suppliers of the next generation of vehicles. Actually, almost all major automakers in the world have unveiled their fuel cell vehicles in the past few years, such as Honda FCX Clarity [6,7], Toyota FCV-R [8,9], Mercedes-Benz F-Cell [10–11], and Chevrolet Equinox Fuel Cell [12,13]. The feasibility of driving these candidate vehicles in real-world conditions has been examined by social demonstration programs such as the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" [14,15] by US Department of Energy (DOE), and the "Japan Hydrogen Fuel Cell Project (JHFC)" by Japan [16]. Most of the automakers are planning to enter the fuel cell vehicle market around 2015. Before entering the market, it is important to understand that the energy, environmental, and economic impacts of the hydrogen-based transportation system will be compared with the conventional petroleum-based system, which could enrich the information available for the public, industry and government to make well-informed decisions. The present work therefore sets the objective to examine the effects of replacing conventional gasoline vehicles (GVs) by hydrogen FCVs on the lifecycle greenhouse gas (GHG) emission and the energy consumption.

Hydrogen should be produced using other primary energy sources. As shown in Fig. 1 [17], about 49% hydrogen produced worldwide is derived from natural gas, primarily via steam methane reforming (SMR). The remaining hydrogen is produced from oil (29%), most of which is consumed in the applications of petroleum refineries, from coal (18%) primarily for the manufacture of ammonia, with the remaining 4% via water electrolysis. That is more than 95% hydrogen produced worldwide is still derived from carbon-based fossil fuels. Consequently, in a hydrogen-based fuel cell vehicle, the majority of GHG emissions and energy consumption would occur before the hydrogen reaches the fuel cells. Therefore, it should carefully consider the life-cycle performance of hydrogen supply system in the fuel cell vehicle application. As shown in Table 1, several likely distributed and centralized hydrogen pathways using renewable and non-renewable energy sources are studied in this work, including the steam reforming of natural gas and corn ethanol and water electrolysis using grid generation and solar electricity at the distributed stations, and coal gasification with and without carbon sequestration in the central plants. The pathway of petroleum to gasoline for GV application serves as the baseline case to which the above hydrogen pathways for FCV application are compared. Since the battery electric vehicles (BEVs) have received a great interest recently and might be competitive against the FCVs in terms of energy and emission reduction benefits, they are included for comparison.

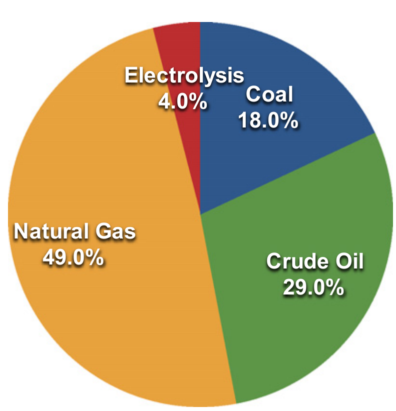

Fig. 1. Feedstock share of global hydrogen production.

Table 1
Fuel pathways associated with the vehicle technologies.

Feedstocks	Fuel processes	Fuels	Scale	Vehicles
Petroleum	Refinery	Gasoline	–	GV
Fuel complexity	Combustion, nuclear reaction…	Electricity	–	BEV
Natural gas	Reforming	H_2	Distributed	FCV
Corn-ethanol	Fermentation/Reforming	H_2	Distributed	FCV
Fuel complexity	Electrolysis	H_2	Distributed	FCV
Solar	Electrolysis	H_2	Distributed	FCV
Coal	Gasification	H_2	Central	FCV
Coal with CCS	Gasification	H_2	Central	FCV

2. Hydrogen pathways

2.1. Hydrogen from natural gas

Fig. 2 shows a simplified block flow diagram of the hydrogen from the natural gas reforming. The feedstock is first desulfurized by hydro-desulfurization and H_2S removal to reduce the sulfur levels to protect catalysts used in the downstream reforming process. After desulfurization, SMR reaction is carried out to convert methane and steam to a hydrogen rich reformate stream within a compact furnace at 800–900 °C temperature and 25–35 atm pressure in the presence of a nickel catalyst according to the following reactions:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (1)$$

The SMR reaction is a highly endothermic process and the heat required for reaction (1) is obtained by the combustion of fuel gas and purged tailgas from the pressure swing adsorption (PSA) unit. Following the reforming step the synthesis gas is cooled and then fed into the WGS reactor to produce additional hydrogen via the water–gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (2)$$

Subsequently, the hydrogen is purified by means of the PSA unit consisting of several vessels filled with selected adsorbents. It reaches hydrogen purities higher than 99.99% by volume and CO impurities of less than 1 ppm (volumetric) fulfilling the fuel specifications for FCV applications. As shown in Table 2, the energy efficiency of hydrogen production via natural gas reforming at the distributed station, including auxiliaries, but excluding hydrogen pressurization, is assumed as 70.5%.

2.2. Hydrogen from electrolysis

Electrolysis opens the door to hydrogen production from any primary energy source that can be used for electricity generation. Currently, three types of electrolytic technologies under consideration for hydrogen production are classified: the alkaline electrolyzer that uses potassium hydroxide (KOH) solutions, the polymer electrolyte membrane (PEM) electrolyzers, and the ceramic oxide electrolyzer. Among them, alkaline electrolysis is the most mature industrial technology. The theoretical maximum electrolysis efficiency is about 85%, but current electrolysis is in general less efficient. Some sources suggest an efficiency of 63.5% (LHV) for the decentralized electrolyzer of capacity 20 $kgH_2\text{-}h^{-1}$ (or 120 cars a day), including auxiliary loads other than compression

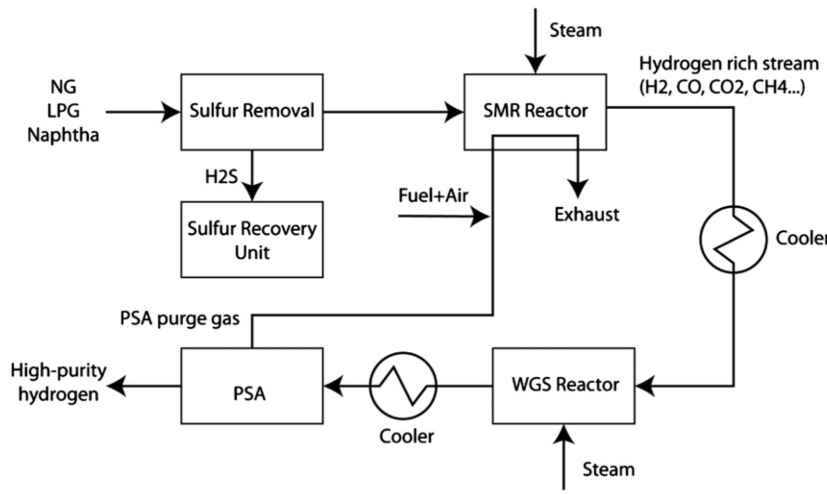

Fig. 2. Simplified block flow diagram for hydrogen from natural gas.

Table 2
Energy efficiencies for natural gas to hydrogen pathways.

Stages	**Efficiency** (%)
NG recovery	97.5
NG processing	97.5
GH2 compression	94.0
GH2 production (reforming)	70.5

Table 5
Energy efficiencies for fuel mix-to-electricity in Taiwan.

Items	**Efficiency** (%)
Residual oil utility boiler efficiency	34.8
NG utility boiler efficiency	34.8
NG simple cycle turbine efficiency	33.1
NG combined cycle turbine efficiency	55.0
Coal utility boiler efficiency	34.1
Electricity transmission and distribution loss	8.0

Table 3
Energy efficiencies from electrolysis to hydrogen pathways.

Stages	**Efficiency** (%)
H_2 production at refueling stations (electrolysis)	71.5
H_2 compression (for GH2): electric compressors	94.0

Table 4
Fuel mix for average electric generation in Taiwan.

Sources	**Amount** (GWh)	**Share** (%)
Coal	123,969	49.9
Oil	13,367	3.8
Natural gas	48,364	24.6
Nuclear power	40,827	16.9
Biomass	589	1.5
Other	3437	3.4
Total	238,326	100

[18,19]. As shown in Table 3, the current model assumes the electrolysis efficiency to be 71.5%. This efficiency difference (63.5% vs. 71.5%) may be explained by the differences between working and test conditions.

The energy sources used for electricity generation embody the most important factor for determining energy use and GHG emissions of electrolysis hydrogen. In the present work, two kinds of electricity sources are employed for electrolysis hydrogen, i.e., grid electricity and solar electricity. Table 4 shows the average share of the fuel sources of electric generation in Taiwan [20], while the efficiency of generation of various fuels are shown in Table 5. Based on the data shown in Tables 4 and 5, the model calculates the carbon intensity of the grid electricity ($gCO_2e\text{-}kWh^{-1}$) for hydrogen production by electrolysis. For electricity delivered to refueling stations, the loss for electric transmission and distribution is assumed to be 5%, Taiwan's average loss. Note that when the solar electricity is used without grid backup, the electrolysis presents non-carbon-emitting hydrogen production. In our calculations, the conversion efficiency from renewable energy sources to electricity is assumed to be 100% because, for renewable sources, resource consumption is not a concern, and there are not any process fuel combustion emissions.

2.3. Hydrogen form coal gasification

Coal is usually regarded as a dirty fuel due to its high air pollution and GHG emissions when combusted. However, the resources of coal will outlast oil and natural gas by centuries. Therefore, it is urgent to shift coal toward a clean hydrogen energy source by developing environmentally benign coal technologies that can lead to high-energy conversion efficiencies and low GHG emissions as compared to conventional coal fired power plant. Fig. 3 shows a simplified block flow diagram of a hydrogen production from coal gasification. Hydrogen is produced from coal by gasification followed by processing the resulting synthesis gas using currently available technologies. Although a complex process, it is a mature and cost-effective technology [21]. As shown in this figure, the prepared coal is first gasified with steam and oxygen, which is highly exothermic, with temperatures controlled by the addition of steam. Increasing the temperature in the gasifier initiates devolatilization and breaking of weaker chemical bonds to yield tars, oils, phenols, and hydrocarbon gases. These products generally further react to form a synthesis gas consisting mainly of carbon monoxide and hydrogen, with some carbon oxide. The synthesis gas is cooled and then enters the sour water–gas shift (WGS) reactor where shift

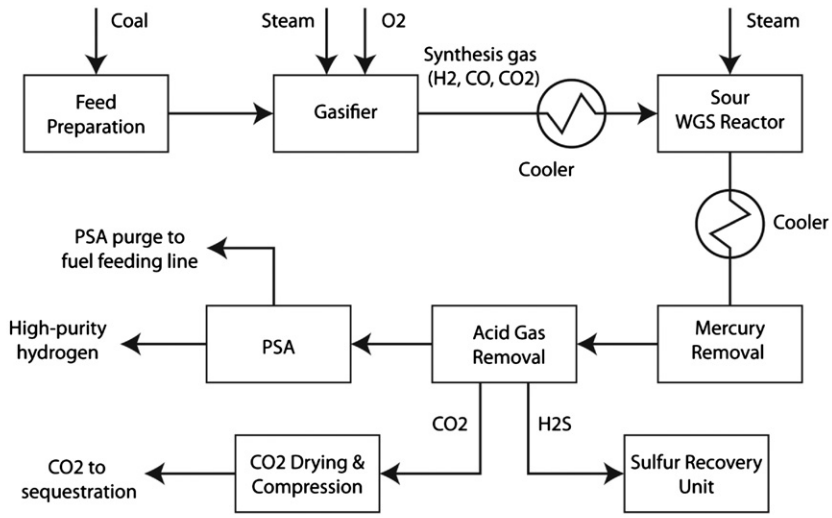

Fig. 3. Simplified block flow diagram of hydrogen from coal gasification, with CCS.

Table 6
Energy efficiency and energy use for coal to hydrogen pathways.

Items	Data
Coal mining and cleaning	99.3%
H_2 production efficiency of coal gasification in central plants: without steam or electricity cogeneration	62.0%
Refueling stations compression efficiency for GH2 received from central plants: NG compressors	85.5%
Refueling stations compression efficiency for GH2 received from central plants: electric compressors	93.9%
Energy use for CO_2 sequestration: kWh per ton of C captured in central plants, coal as feedstock	250 kWh $(tC)^{-1}$

Table 7
Energy efficiencies for corn-ethanol to hydrogen pathways.

Stages	Items	Data
Corn to ethanol	CO_2 emissions from domestic land use change by corn farming	407 g/bushel
	CO_2 emissions from foreign land use change by corn farming	742 g/bushel
	Corn farming energy use	9142 Btu/bushel
	Ethanol production energy use: dry mill	26,856 Btu/gallon
	Ethanol production energy use: wet mill	47,409 Btu/gallon
	Corn ethanol, share of ethanol plant type, dry milling plant	88.6%
	Corn ethanol, share of ethanol plant type, wet milling plant	11.4%
	Share of process fuels in dry mill ethanol plant: natural gas	92%
	Share of process fuels in dry mill ethanol plant: coal	8%
	Share of process fuels in wet mill ethanol plant: natural gas	72.5%
	Share of process fuels in dry mill ethanol plant: coal	27.5%
Ethanol to hydrogen	Refueling station production efficiency: EtOH as feedstock	67.5%
	Refueling stations compression efficiency for station produced GH2: NG compressors	85.5%
	Refueling stations compression efficiency for station produced GH2: electric compressors	93.9%

catalysts convert CO and steam to CO_2 and additional H_2 (Eq. (2)). The synthesis gas from sour WGS is then cooled before mercury removal. Then, carbon dioxide as well as the hydrogen sulfide is removed in an acid gas removal (AGR) reactor. Finally, the sweet synthesis gas from AGR reactor is routed through the PSA unit to recover 99.99% pure hydrogen products.

Note that the production of hydrogen by coal gasification is not suited to decentralized production, because it relies on economies of scale, and carbon capture and storage (CCS) in small-scale systems would be expensive and difficult. Therefore, the present model assumes that coal-based GH2 is produced in central plants via gasification. As shown in Table 6, the energy efficiencies for coal-based hydrogen production is 62%. The energy use for carbon sequestration is 250 kWh per ton of carbon captured. Note also that, in recent years, increasing attention has been paid to the co-production of electricity and hydrogen fuels from coal, as these capital-intensive plants offer significant economies of scale, high capacity factors and high levels of overall efficiency [22–24]. In addition, the large-scale production of hydrogen from integrated gasification combined cycle (IGCC) plants appears to be a particularly attractive option for the centralized production of hydrogen. IGCC plants offer the potential for the efficient and flexible cogeneration of electricity and hydrogen from coal, with cheap CO_2 separation for CCS.

2.4. Hydrogen from bioethanol

Liquid bioethanol is one of the most promised and economical renewable fuels. It can be converted into hydrogen simply and with high efficiency. Reforming bioethanol to hydrogen is very similar to reforming natural gas. The reaction pathways and thermodynamics of ethanol steam reforming have been studied

extensively recently [25–29]. The liquid bioethanol is reacted with steam at high temperatures in the presence of a catalyst to produce a reformate gas composed mostly of hydrogen and carbon monoxide [30–33].

$$C_2H_5OH + H_2O \rightarrow 2CO + 4H_2 \quad (3)$$

Then, reacting the carbon monoxide with high-temperature steam in the WSG reactor produces additional hydrogen and carbon dioxide (Eq. (2)). The hydrogen is separated out and purified thereafter. In the present model, the bioethanol is produced at large, central facilities located near the cornfield to take advantage of economies of scale and reduce the cost of transporting the feedstock. The liquid corn ethanol is then transported to the distributed refueling stations for reforming to hydrogen. It is anticipated that above distributed reforming of bioethanol could be commercial during the transition to hydrogen economy and used in the mid- and long-term time frames. Table 7 summarizes the energy efficiencies for corn ethanol to hydrogen pathway in the present model. It includes the farming energy used in planting, harvesting and fertilizer, transportation, and processing of corn into ethanol [28]. It is interesting to note that the cost of water removal after fermentation should be considerably reduced when ethanol is used in reforming hydrogen for fuel cell application rather than as a fuel mixed with gasoline. Further, combustion used has only about 20% efficiency for transportation as compared with up to 60% efficiency for a fuel cell.

3. Methodology

In the present work, the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed by Argonne National Laboratory is employed to examine the life-cycle energy and emission of fuel cell vehicle technologies along with hydrogen fuels. The principle of the model has been described in detail elsewhere [34–40] and is not elaborated on here. In the present model, probability-based distribution functions are developed to describe energy use and emissions for individual operations in fuel production and transportation processes, as well as vehicle operations. Three GHGs are combined together with their global warming potentials (GWPs) to calculate CO_2-equivalent GHG emissions, i.e., 1 for CO_2, 23 for CH_4, and 296 for N_2O, which are recommended by the Intergovernmental Panel on Climate Change for the 100-year time horizon [41].

As depicted in Fig. 4, the fuel-cycle analysis could be divided into three stages, i.e., the feedstock (or primary energy) stage, the fuel stage, and the vehicle operation stage. The feedstock together with fuel stages is called as the well-to-pump (WTP) stage, while the vehicle operation is called as the pump-to-wheels (PTW) stage. In the present work, the results of WTW energy and emission for fuel cell vehicles are presented separately for WTP and PTW stages. Note that the present study considers the operation-related energy and emissions only. That is, the energy and emissions related to operational activities for the fuel process and vehicle are included. On the other hand, those of infrastructure-related energy consumption and

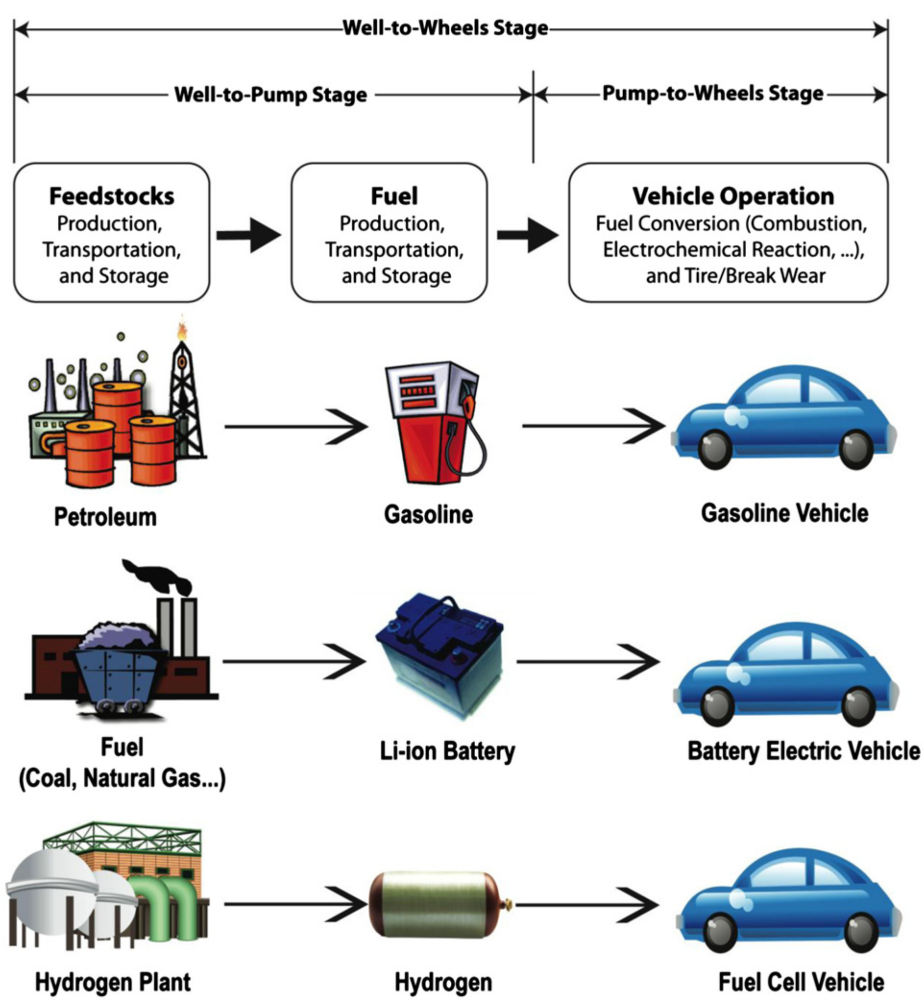

Fig. 4. Stages of vehicle/fuel systems covered in the present LCA model.

GHG emissions (such as energy and emissions associated with building roads, plants, and plant equipment) are not included for any of the pathways evaluated.

4. Results and discussion

4.1. Fuel economy

The fuel economy is a key PTW parameter in determining the WTW energy consumption and GHG emissions associated with a vehicle/fuel system. In general, the fuel economy of a vehicle has two categories, i.e., a city estimate and a highway estimate [42]. A city estimate represents urban driving, in which a vehicle is started in the morning (after being parked all night) and driven in stop-and-go traffic. A highway estimate that represents a mixture of rural and interstate highway driving in a warmed-up vehicle, typical of longer trips in free-flowing traffic. The present fuel economies are based on the combination of the above estimates, and all vehicles are tested in the same manner to allow fair comparisons.

Fig. 5 and Table 8 depict the fuel economies for three types of commercial midsize passenger cars, i.e., GV, BEV, and FCV. As shown in Table 8, the model of GV selected for comparison is Toyota Camry A-S6. It has a fuel economy of 28 mpg in the combined mode. As for the BEVs, the first model of lithium-ion battery based electrical vehicle accessible in the market, Nissan Leaf, is taken for life-cycle analysis. It has a fuel economy of 99 mpg in the combined mode. As for the FCVs, the proton exchange membrane (PEM) fuel cell is best suited for vehicular applications [43] among various fuel cell types. In general, the fuel economy for FCVs is dependent on the automatic control [44], operating temperature [45–47], and many other operating characteristics [48–50]. Actually, the FCVs do not reach the mass market yet, and only a limited number is available for sale or lease to demonstration fleets in areas with a readily accessible hydrogen supply. In this work, the Honda Clarity is selected for the life-cycle analysis. It is seen from Fig. 5, the fuel economy for the BEV is considerably higher than that of the GV because the energy efficiency of the electric motor is significantly higher than that of the IEC. The lower fuel economy of FCVs as compared to that of BEVs is because of the electrification loss caused by the electrochemical reaction in the fuel cell system.

4.2. WTP efficiency

Figs. 6 and 7 show the energy consumption (Btu-kgH_2^{-1}) and the GHG emission (kgGHG-kgH_2^{-1}) of various hydrogen pathways, respectively. It is seen from these two figures, the hydrogen production from the water electrolysis by using the grid electricity (EZ-H2 (grid)) consumes the most energy and simultaneously produces the largest GHG emission among the hydrogen pathways. In contrast, the hydrogen production from electrolysis by using the solar electricity (EZ-H2 (PV)) has the least total energy consumption as well as the GHG emission.

Fig. 8 further shows the WTP efficiency of the six hydrogen pathways. The WTP efficiency for the fuel pathways of petroleum-to-gasoline and the fuel mix-to-electricity (i.e., grid electricity) is

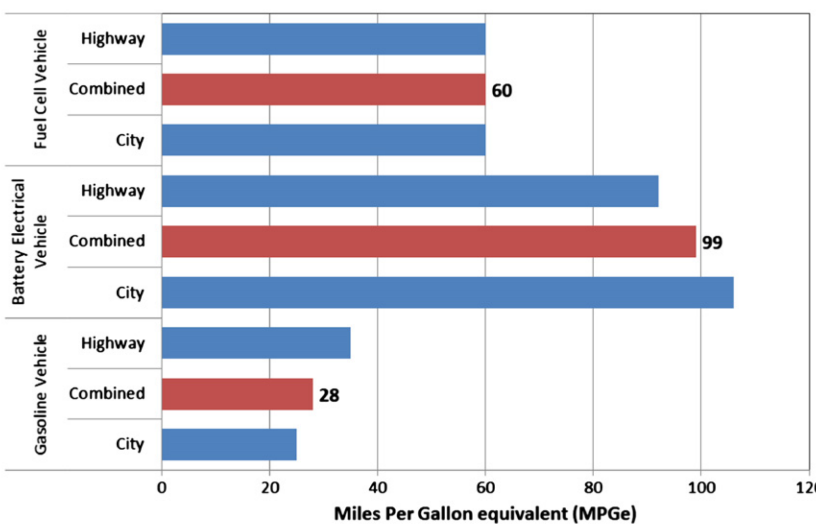

Fig. 5. Fuel economy of three types of vehicles.

Table 8
Fuel economies of various types of vehicles.

Type	Gasoline vehicle	Electric vehicle	Fuel cell vehicle
Brand	Toyota Camry	Nissan Leaf	Honda Clarity
Fuel economy (Combined mode)	26 MPG	99 MPG	60 MPG (MPKG)
Photo			

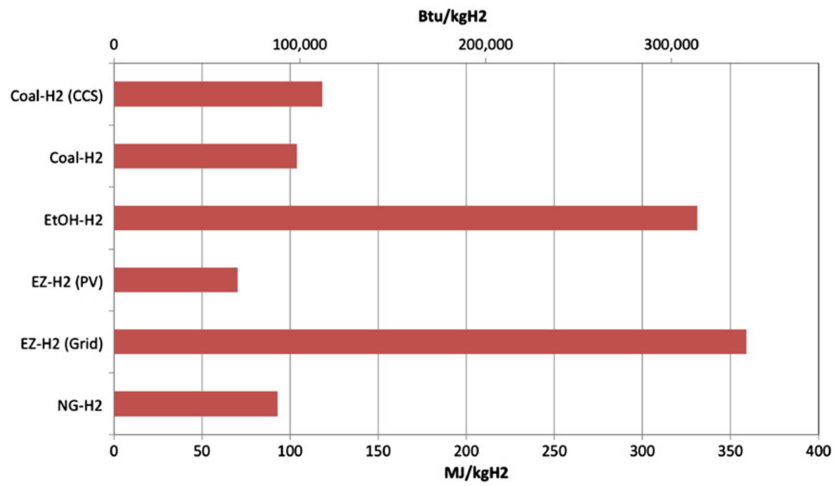

Fig. 6. Energy requirements for hydrogen production (per kilogram hydrogen).

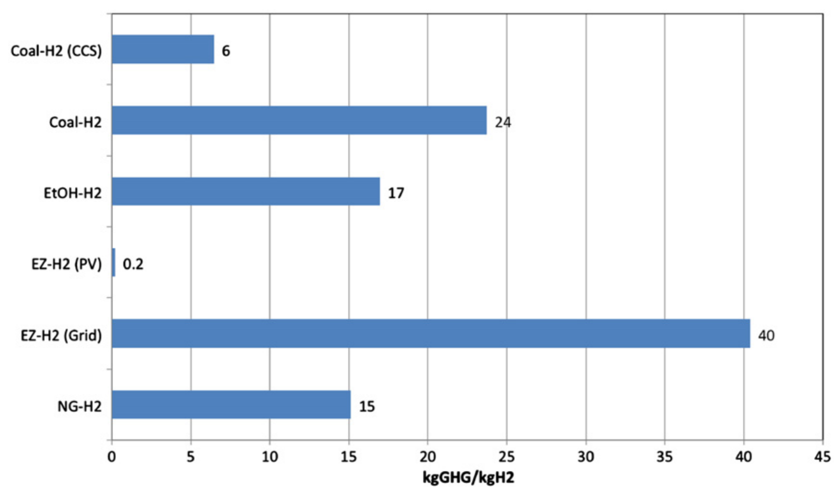

Fig. 7. Total GHG emissions of the hydrogen production (per kilogram hydrogen).

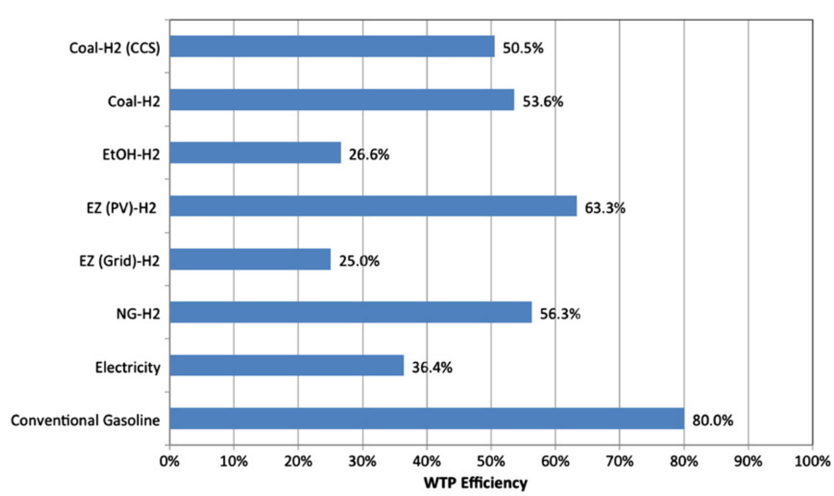

Fig. 8. Well-to-pump energy efficiencies for various fuel pathways.

also included for comparison. It is seen from this figure that the fuel pathway of gasoline from petroleum refinery for GV applications has the highest WTP efficiency among the investigated fuel pathways, typically about 80%. The WTP efficiency of grid electricity for charging the BEVs is less than half of that of gasoline from petroleum refinery, i.e., only 36.4%. Among the six hydrogen pathways, the water electrolysis using the photovoltaics has the highest WTP efficiency (63.3%), while the hydrogen from water electrolysis using the grid electricity has the lowest WTP efficiency (25%). Two significant efficiency losses occurring in

electricity generation and water electrolysis hydrogen production are the subjects of the lowest WTP efficiency.

4.3. Stage and total energy consumptions

Fig. 9 compares the total and stage energy consumptions for various fuel/vehicle systems. It is seen from this figure that although the energy consumption for the BEVs is higher than that for the GVs in the stage of fuel process (feedstock and fuel), the BEVs are more efficient in the vehicle operation than the GVs that reduces their total energy consumption.

It is further seen from this figure that, except for the hydrogen pathways of the corn ethanol reforming and the water electrolysis by using grid electricity, the FCVs fuelled by hydrogen have energy-reduction benefits as compared to the GVs. The FCVs fuelled by the corn-ethanol hydrogen have significant energy consumption in the feedstock process (blue bar), resulting in large total energy consumption. Basically, the energy analysis of the corn ethanol is based on the energy in harvested biomass as well as that of the ethanol process (Table 7). That is the energy consumption in the feedstock stage accounts for the energy required for farming and processing corn into ethanol in addition to the energy in the corn kernels, which results in a significant total energy use for ethanol-based hydrogen production.

Attention is now turning to the FCVs fuelled by electrolysis hydrogen. The moderate fuel economy of FCVs (PTW efficiency) cannot offset the substantial energy consumption due to poor WTP efficiency of water electrolysis using the grid electricity (Fig. 8). In contrast, for the fuel pathways involving renewable electricity, only the generated electricity is taken into account. The present model excludes the primary energy in renewable electricity which is because the renewable primary energy is not subject to energy resource depletion. If the primary energy for renewable electricity generation is included, the renewable electricity system would result in substantial WTW energy use.

4.4. Stage and total GHG emissions

Fig. 10 shows the stage and total GHG emissions for various fuel/vehicle systems. For CO_2 emissions, the present model takes a carbon-balance approach. That is, the carbon in CO_2 emissions is equal to the carbon contained in the fuel burned minus the carbon contained in combustion emissions of VOC, CO, and CH_4. And, the total GHG emissions, i.e., CO_2-equivalent emissions, include CO_2, CH_4, and N_2O, which are major GHGs from motor vehicles.

As shown in Fig. 10, the GVs have a significant GHG emission in the vehicle operation stage. In contrast, both the BEVs and the FCVs have zero emission during the vehicle operation. The FCVs could reduce the total GHG emission as compared to the GVs except for the hydrogen option of electrolysis using the grid electricity. Comparing the two electrolysis hydrogen pathways in

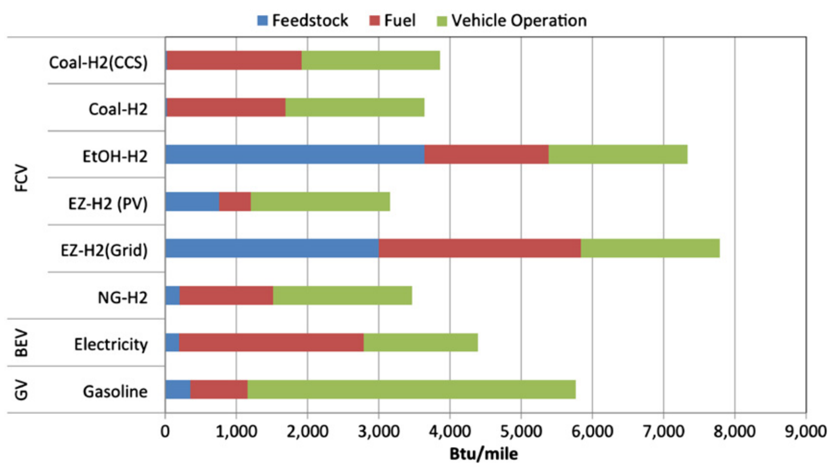

Fig. 9. Total and stage energy consumptions for various fuel/vehicle systems.

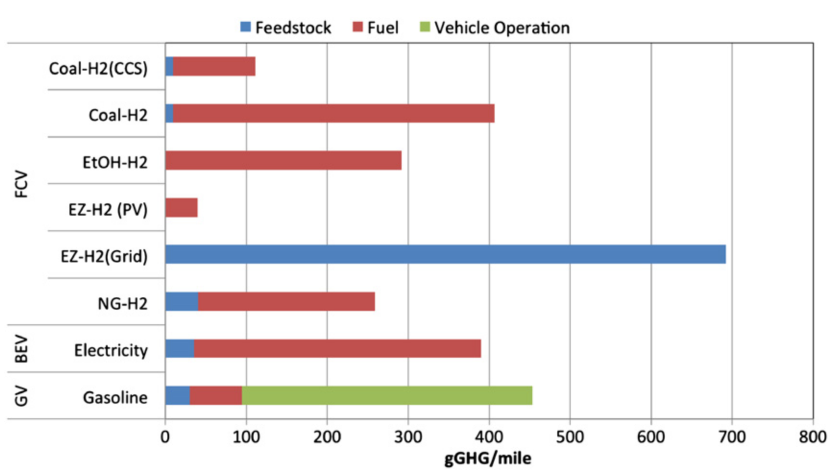

Fig. 10. Total and stage GHG emissions for various fuel/vehicle systems.

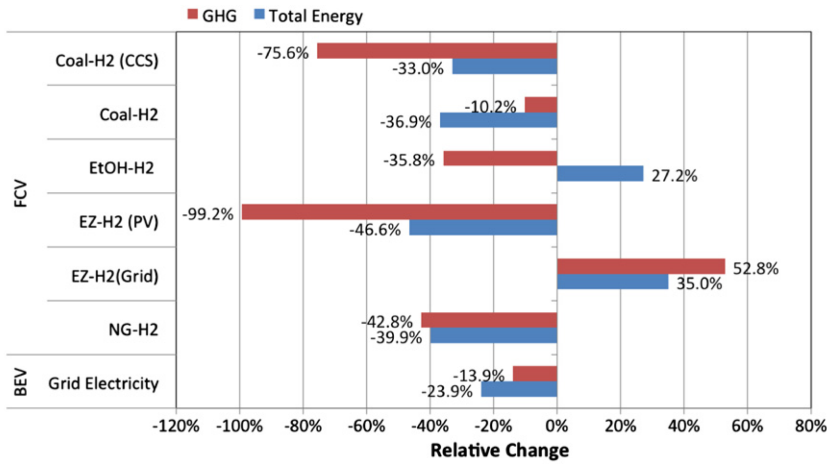

Fig. 11. Relative changes of total energy and GHG emissions for various fuel/vehicle systems as compared to the GVs.

Fig. 10 could illustrate the importance of electricity sources for electrolysis hydrogen in the total GHG emissions for FCVs. The FCVs using the electrolysis hydrogen could reduce the GHG emission where renewable electricity is available for hydrogen production even though it is inefficient to produce hydrogen via electrolysis. As further shown in Fig. 10, The FCVs fuelled with the renewable hydrogen derived from corn ethanol achieves only a slight GHG emission reduction as compared with the GVs. Basically, the fuel processes for corn ethanol consume a significant amount of fossil fuels (resulting in GHG emissions) and the cornfields produce a large amount of N_2O emissions from nitrogen nitrification and de-nitrification as well. Note also that the coal gasification with CCS is a potential hydrogen option for FCVs since it significantly reduces the GHG emission and accompanies the moderate energy consumption (Fig. 9).

4.5. Change in total energy and GHG emissions

Fig. 11 shows the relative changes in the total energy consumption and GHG emissions for various fuel/vehicle systems as compared to the baseline case of GVs. It is clearly seen from Fig. 11 that the FCVs fuelled with electrolysis hydrogen using grid electricity suffer for the increase in the total energy consumption by 35% in addition to the increase in the GHG emission by 27.2%. In contrast, the FCVs fuelled with hydrogen from PV electrolysis are the most promising in energy conservation as well as the GHG emission reduction. It reduces the total energy consumption and the GHG emissions up to 46.6% and 99.2%, respectively. As for another renewable option of corn ethanol reforming, the FCVs have the benefit of reduction in the GHG emission by 35.8%, but suffer for the increase in the total energy by 27.2% as compared with the GVs.

4.6. Cost concerns

Fig. 12 shows the production cost status of several distributed hydrogen production pathways. Note that the costs shown include all delivery and dispensing costs, but do not include taxes. In addition, projections of distributed costs assume station capacities of 1500 kg hydrogen per day, with 500 stations built per year [51,52].

The hydrogen threshold cost (HTC) shown in Fig. 12, with a range of US$2 to US$4 per gallon gasoline equivalent (gge), represents the values at which hydrogen is competitive with gasoline. It includes consideration of the volatility in the price of gasoline as well as the range of fuel economies possible with FCVs

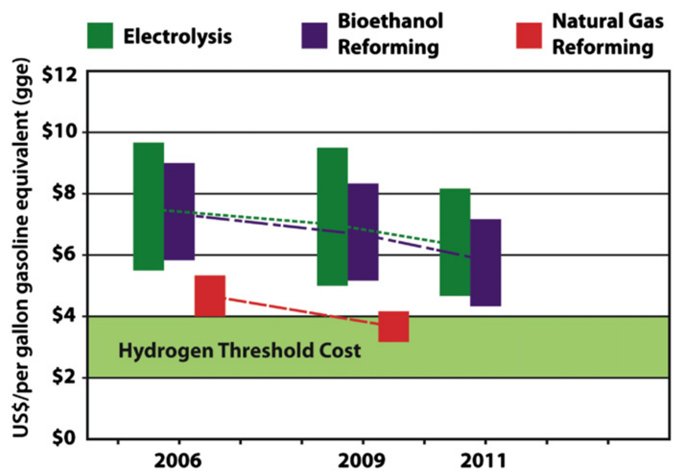

Fig. 12. Hydrogen production cost status [51].

in comparison with other vehicle options. It is seen from this figure that significant progress in cost down has already been made in the above hydrogen production pathways during the past few years. The natural gas reforming has achieved the threshold cost in 2009. However, hydrogen production from the bioethanol reforming and water electrolysis is still more costly than the target. As noted by the above results, FCVs fuelled with hydrogen from renewable energy-based electrolysis show the greatest potential for minimizing negative energy and environmental impacts of vehicle/fuel supply systems. However, with regard to economic concerns, fuel costs are higher for electrolysis-based hydrogen than for the conventional gasoline at the current level of technology maturity. In combination of the next most environmentally benign source of hydrogen, and the competitive cost of gasoline, the natural gas SMR technology is regarded as the most promising hydrogen pathway in the near-term of penetration to the market.

5. Conclusions

A life-cycle analysis of energy consumption and GHG emission of FCVs has been carried out in the present study. Several potential hydrogen options using renewable and non-renewable energy sources are discussed, including steam reforming of natural gas and corn ethanol, water electrolysis using grid and

solar electricity, and coal gasification with and without carbon sequestration. The WTW efficiency of FCVs for various hydrogen production options is compared with that of the conventional GVs and BEVs. Main findings from the present LCA research are concluded below.

1. FCVs fuelled with electrolysis hydrogen from renewable electrification show the greatest capability for minimizing negative energy and environmental impacts. However, the fuel costs retard its commercial viability. The fuel cost for electrolysis-based FCVs is significantly higher than that for the petroleum-based GVs at the current level of technology maturity.
2. FCVs fuelled with electrolysis hydrogen using grid electricity are not recommended because of the significant energy consumption and GHG emissions in the feedstock stage, which are even higher than those of the GVs.
3. FCVs fuelled with the hydrogen from corn-ethanol reforming offer a low GHG emission but suffer for the significant energy consumption.
4. Hydrogen from NG-based SMR is likely to be the primary mode of production for the initial introduction of FCVs. The resulting life-cycle emissions per mile traveled are about 42% less than those from GVs, and 21% less than those from BEVs. Most importantly, its cost has been competitive with gasoline.

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